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DESIGN OF A 1 KW PROTON EXCHANGE MEMBRANE FUEL CELL FOR SOLAR HYDROGEN ECO-HOUSE

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Abstract

The objective of this study is to design the application system of 1 kW PEMFC to support the ECO-House Solar Hydrogen Energy System. Fuel cell is an electrochemical reactor to convert the chemical energy (H_2) as fuel substance, with oxygen (O_2), to yield water, electrical energy, and heat as a by-product. The system planning of the fuel cell application, is to design the fuel cell operational supporting unit network, i.e.: The air supply unit as oxygen source, in this case the ambient air in Malaysia possess the humidity sufficient for operating the fuel cell, and thus the air only be filtered, pressed by a compressor/blower, and is received in feed tank to keep the stream continuity. The hydrogen unit as fuel substance, uses the hydrogen produced from water electrolysis with 99.9% purity, has been kept in a tank with 150-200 bar pressure, so as before feeding a pressure reduction is undertaken using the pressure regulator valve and is humidified in a cooling water tank, while the unreacted hydrogen is to be recycled and to be fed together with a fresh feeding. The cooling unit employs deionized water in order to utilize for hydrogen humidification, and the water from the tank is pumped to cool the fuel cell stack, while the used water is then cooling in the radiator, and moreover to be incorporated in the tank. The water stream is to be advantaged for the unreacted hydrogen circulation with the jet ejector. The evaluation results has been conducted using the MATLAB software and the electric efficiency found to be 26.46 % to the power of fresh hydrogen. When the radiator cooling is carried out without fan (natural convection) with a contact surface enlarged, thus the electric efficiency becomes increased to 27.69 %.

Abstrak

Tujuan studi ini adalah merancang system penggunaan 1 kW PEMFC, untuk mendukung ECO-House Solar Hydrogen Energy System. Fuel cell adalah reactor electrokimia guna mengkonversi energy kimia (H_2) sebagai bahan bakar, dengan oksidan (O_2), menghasilkan air, energy elektrik, dan panas sebagai hasil samping. Perancangan system penggunaan fuel cell, adalah merancang susunan unit pendukung operasi fuel cell, yaitu: Unit suplay udara sebagai sumber oksidan, dalam hal ini udara luar di Malaysia mempunyai kelembaban yang cukup untuk operasi fuel cell, maka udara hanya di filter, ditekan dengan kompresor/blower, dan ditampung pada tangki pengumpan untuk menjaga kontinuitas aliran. Unit Hydrogen sebagai bahan bakar, menggunakan hydrogen hasil electrolisa air dengan kadar 99,9 %, disimpan dalam tangki bertekanan 150-200 bar, sehingga sebelum diumpankan dilakukan penurunan tekanan dengan pressure regulator dan dihumidifikasi dalam tangki air pendingin, hydrogen yang tidak bereaksi direcycle dan diumpankan bersama umpan segar. Unit Pendingin, menggunakan air deionisasi, karena dipakai juga untuk humidifikasi hydrogen, air dari tangki dipompa untuk pendingin fuel cells stack, air bekas pendingin didinginkan dalam radiator, selanjutnya dimasukan dalam tangki. Aliran air dimanfaatkan untuk sirkulasi hydrogen yang tidak bereaksi dengan jet ejector. Hasil perhitungan yang dilakukan dengan bantuan software MATLAB didapatkan electric efficiency 26,46 %. terhadap power hydrogen segar. Kalau pendinginan radiator dilakukan tanpa fan (natural convection), dengan luas permukaan kontak diperbesar, maka electric efficiency 27,69 %.

Keyword: Fuel Cell System, PEMFC, Hydrogen Energy, Solar.

1. Introduction

Eco House, one of example environmental friendly dwellings future, and also as a solar energy laboratory in engineering faculty of UKM in Malaysia. The energy system applied for Solar Hydrogen Energy System (SHES), inside existed the fuel cell subsystem, which has the function to convert the chemical energy into

electricity. The fuel cell subsystem design is to obtain the configuration for yielding optimum electrical efficiency, and therefore to support the electrical efficiency system in Eco House solar hydrogen energy.
Fuel cells are electrochemical devices that convert the chemical energy of a reaction directly into electrical energy. The basic physical structure or building block of a fuel cell consists of an electrolyte layer in contact with a porous anode and cathode on either side. The electrolyte in **Polymer Electrolyte Membrane Fuel Cell (PEMFC)** is an ion exchange membrane (fluorinated sulfonic acid polymer or other similar polymer) that is an excellent proton conductor. Test results have shown that the cell can operate at very high current densities compared to the other cells. In the case of a hydrogen-oxygen fuel cell, hydrogen (H_2) is the fuel and oxygen (O_2) is the oxidant. The only product is pure water (H_2O), and the total reaction is:

$$H_2(g) + \frac{1}{2}O_2(g) \rightarrow H_2O + electrical\_energy$$

The U-I characteristics of single cell of fuel cell stack can be represented by the following equation:

$$U = U_0 - b.\ln(i) - R.(i) \qquad (1)$$

Where, U is the cell voltage (mV), U_0 the open circuit voltage (mV), I the current density (mA cm^{-2}), b the tafel slope (mV per decade) and R the ohmic resistance (Ω cm^2) of the cell. The tafel slope represents the voltage losses due to activation polarization of both electrodes. The ohmic resistance of the cell as mentioned previously is due to the resistance to flow of protons in the electrolyte membrane, resistance to the flow of electrons through the stack materials and various contact resistances. The values of ohmic resistance, R of each cell in various configurations of the stack varies from 0.228 to 0.338 cm^2. The values of tafel slope, b varies from 85.9 to 122.7mV per decade (S.Giddey et al., 2004). The PEMFC operating temperature range from 60-80°C, operating pressure range from near ambient to 3 bar, and 0-100% relative humidity range for both the air and fuels stream (D.A. Masten; and A.D. Bosco;2003).

2. Fuel cell system design

The fuel cell stack is the heart of the fuel cell system; it cannot work without other support components. Therefore, the success in integrating a fuel cell system relies on the proper operation of each component in the system. Fig. 1 shows a schematic diagram of H_2/air PEMFC system. The support components of the fuel cell system include a humidifier, an air blower or compressor, a humidifier, pressure regulators, a radiator, a hydrogen tank, pipes and fittings. They are grouped into four subsystems and will be discussed in the following sub-section, respectively, i.e. fuel cells stack, hydrogen fueling subsystem, air supply subsystem, water coolant subsystem.

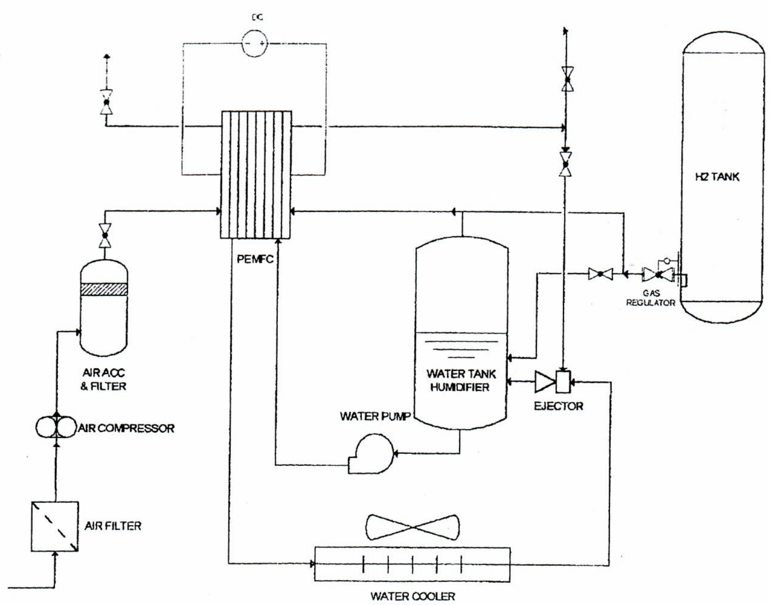

Fig.1. Schematic diagram of H_2/Air PEMFC system in this study

Power balance of System:

$$P_{H_2} = P_{fc} + P_{heat} \qquad (2)$$

$$P_{fc} = P_{out} + P_{pars} = P_{out} + P_{ctrl} + P_{hand} \qquad (3)$$

$$P_{hand} = P_{airComp} + P_{W,Pump} + P_{fan,C} \quad (4)$$

$$P_{out} = P_{fc} - P_{ctrl} - P_{airComp} - P_{W,pump} - P_{fan,C} \quad (5)$$

In this paper, system efficiency is defined as follows: $\eta_{SE} = \frac{P_{out}}{P_{H_2}}$ (6)

P_{H2} = fuel power, which is equal to fuel flow-rate x heating value.

2.1. Fuel cell stack

The stack consists of 25 cells with an active area of 255 cm2, the nominal power are 1. kW. Fig. 2 is I-U characteristic (equation 1). At the power are 1 kW, find of Current density = 390 mA/cm^2, Voltage/Cell = 0.45589 Volt, Voltage of Stack = 11.396 Volt, H_2 cons. = 40.9201 mol/h; Power H_2 in = 3250.8758 Watt, Power of Heat = 2250.8758 Watt.

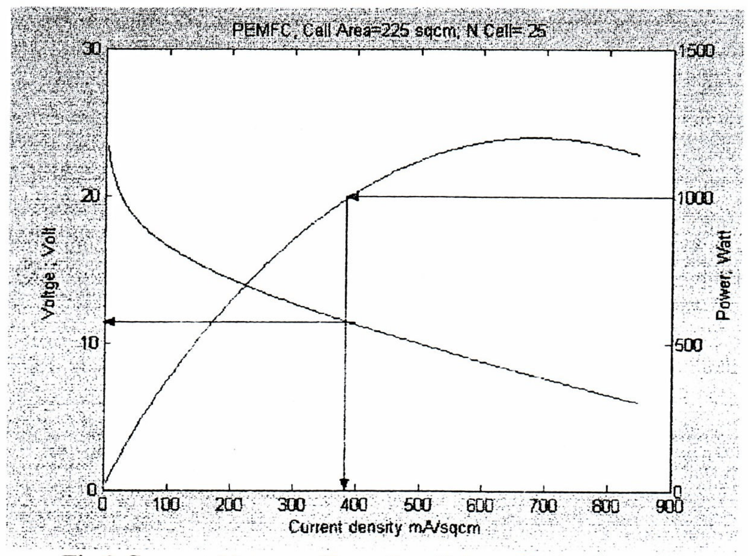

Fig.2 Current-Voltages (Equation 1) for a Fuel cells stack.

2.1.1. Fuel cells stack mass balance.

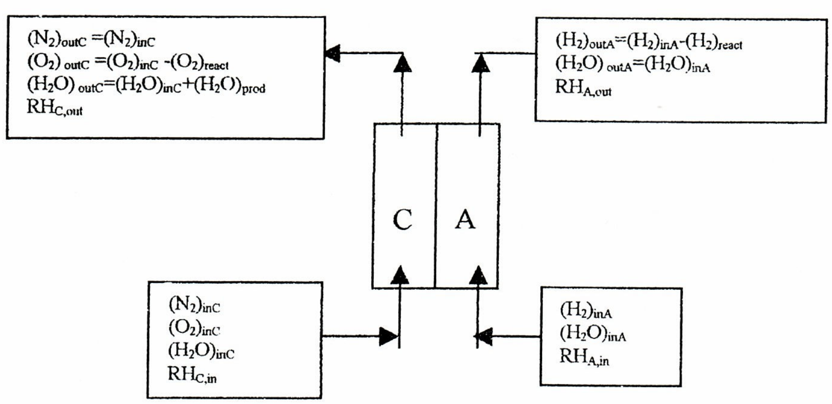

Fig.3. Flowchart of mass balance of the PEMFC

2.1.2. Fuel cells stack heat balance:

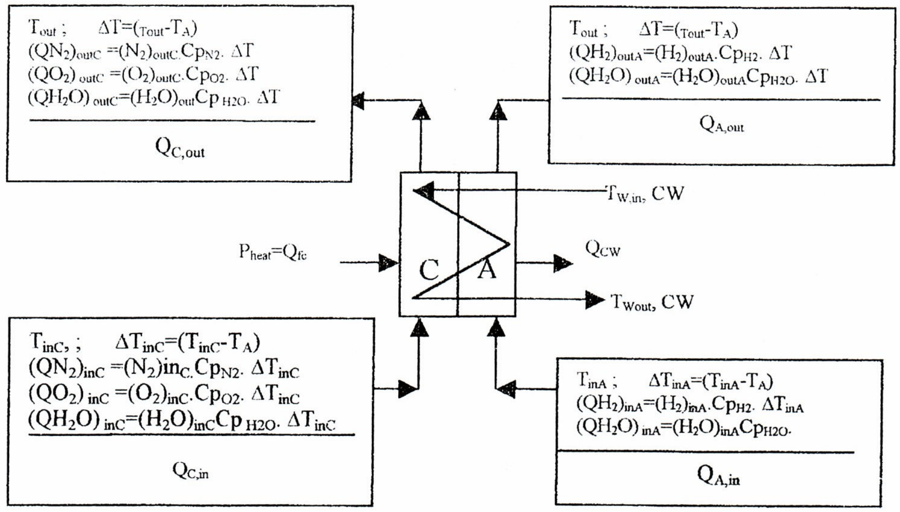

Fig.4. Flowchart of heat balance of the PEMFC

By omitting the heat loss from the surface of Fuel Cell Stack to ambient air, the total heat balance around the FC stack will be as follows: $CW.Cp_W.(T_{Wout} - T_{Win}) = Q_{CW} = Q_{C,in} + Q_{Ain} + Q_{fc} - Q_{Cout} + Q_{Cout}$ (7)

$$CW = \frac{Q_{CW}}{Cp_W.(T_{Wout} - T_{Win})} \tag{8}$$

2.2. Hydrogen fueling

The fuel cell uses pure hydrogen (>99.99%), the result from electrolyzer subsystem in SHES in ECO-house has been kept in vertical cylinder tank with 150-200 Psi. The hydrogen pressure from the feed tank is reduced by a regulator and is swelled in water tank as a humidifier before entering the fuel cell stack. The unreacted hydrogen removed from the fuel cell anode is exhausted by a water jet ejector to be recycled. The hydrogen humidity is adjusted using hydrogen by pass. The hydrogen humidity removed is to be kept below 100 % by adjusting the inlet hydrogen humidity in order to prevent the water sublimation in fuel cell channels in which may diminish the activated specific surface area.

$$RH_{outA} = \frac{(H_2O)_{outA}}{(H_2)_{outA}.Y_{S.mol}}.100\% < 100\% \tag{9}$$

2.3. Air supply

Air is applied for oxygen source (O_2) with assumption dried air contained 21% O_2 and 79% N_2. The nitrogen and oxygen remainders removed from the cathode together with water and heat from the reaction product, and hence the air feeding should be in excess. The ambient air in Malaysia (UKM) from measurement is found to be around 28 – 32°C with relative humidity 56-62%, and therefore in the usage system it does not need humidification. The ambient air is passed through a filter, pressed by a compressor in order to get a pressure a little bit higher than the operation temperature and also the relative humidity of air increased. Before feeding into the fuel cell, it is kept in the accumulator tank or feeding tank to keep the continuity of feeding air stream. The air residue outlet carried water from the reaction product on the cathode, and thus the relative humidity increased to avoid the water sublimation in fuel cell channels, while the relative humidity of air outlet is adjusted to be lower than 100% by arranging the ratio of air velocity (O2) and hydrogen in the feeding tank.

$$RH_{outC} = \frac{(H_2O)_{outC}}{\{(N_2)_{outC} + (O_2)_{outC}\}.Y_{S.mol}}.100\% < 100\% \tag{10}$$

2.4. Water Coolant

The heat produced in the fuel cell stack, partially carried by removed gas, and the most part taken by the cooling water. For cooling the experiment uses deionised water on account of that water also used for hydrogen gas humidifier in water tank. The water is pumped to cool the fuel cell stack, while the used water is cooling in radiator and incorporated into water tank. The inlet water stream into the water tank is to be advantaged to draw the unreacted hydrogen gas by passing via the jet ejector, and furthermore together with fresh hydrogen is to be feeding via the fuel cell anode.

3. Discussion

The hydrogen power converted to heat depends on the fuel cell characteristic, and hence in order to obtain the maximum electric efficiency system can only be carried out by minimizing the parasitic power and unreact hydrogen recycling. In this case the system is carried out to advantage the cooling water stream with jet ejector to circulate hydrogen, and also the ambient water condition had 56-62% relative humidity, therefore it does not need an air humidifier. The removed air from the fuel cell stack carried water as reaction product and directly wastes to the surrounding.

Eq. 1 - 10 has been solved by MATLAB language program. The eq.1 with input power 1 kW, cell area 225 cm, and numbers of cell stack 25, will yield current density, voltage at certain operation temperature (70oC), hydrogen consumption, power of hydrogen and power of heat. The furthermore equation by trial and error, by applying temperature input, relative humidity, ratio of air and hydrogen, entered feeding, it will obtain both feeding velocity as well as cooling water velocity which is used furthermore in order to compute the pump power, compressor as well as fan in radiator, and motor power taken as the power standard. The complete program output from the computer is as follows

```
>> FUELCELL
Cell area, sqcm    =225
Number of cells    = 25
Current density, mA  = 390
Power, watt =1000

CHARACTERISTIC OF FUEL CELL STACK:
Number of Cell    = 24.9974 Cell
Current density   = 390 mAmper
Area of Cell      = 225  sqcm.
Current of Stack  = 87.75 Ampere
Voltage of Cell   = 0.45589  Volt
Voltage of Stack  = 11.396 Volt
H2 cons           = 40.9201 g-mol/h
Power H2 in       = 3250.8758 Watt
Power of FC       = 1000 Watt
Power of Heat     = 2250.8758 Watt
El. Eff.of Stack  = 30.7609 %

RESULT OF HEAT AND MASS BALANCE:
Temp Gas  inlet  = 40  °C
Temp Gas outlet  = 70  °C
RH Air inlet     = 70 %
RH H2 inlet      = 70 %
RH Air outlet    = 82.2632 %
RH H2 outlet     = 87.5739 %
H2 feed          = 49.1041 g-mol/h
Water in feed H2 = 1.33 g-mol/h
O2 feed          = 73.6562 g-mol/h
N2 in O2 feed    = 277.0876 g-mol/h
Water in O2 feed = 9.5 g-mol/h
H2 outlet        = 8.184 g-mol/h
Water in H2 outlet = 1.33 g-mol/h
O2 outlet        = 53.1961 g-mol/h
N2 in O2 outlet  = 277.0876 g-mol/h
Water in O2 outlet = 50.4201 g-mol/h
Coolant Heat load. = 7760492.8547 J/h
Water coolant    = 12.9342 liter/min, Temp. Diff. of water 10 °C
```

The 2000 l/h standard pump is taken with motor power 40 W, compressor with motor power 60 W and fan 40 W, and hence the electric efficiency of system found to be 26.46 %. When the coolant air radiator without fan (natural convection), and the contact surface enlarged, thus the electric efficiency will be 27.69%.

4. Conclusions

A 1 kW PEMFC stack is arranged from 25 cells with surface area of cell 225 cm^2 at 70°C temperature operation, and the electric efficiency of stack is found to be 30,76%. Depending on the fuel cell characteristics, evaluation results of PEMFC characteristic with eq.1, it will give results as follows: current density = 390 mA/cm^2, Voltage/Cell = 0.45589 V, Voltage of Stack = 11.396 V, H_2 consumption = 40.9201 mol/h; Power H_2 in = 3250.8758 Watt, Power of FC = 1000 Watt, Power of Heat = 2250.8758 Watt.

In order to obtain the optimum electric efficiency system, it can only be done, by using a configuration design system with minimizing the parasitic power. In this study, the electric efficiency system is found to be 26.46 %. When the radiator cooling using the natural convection (without fan), and the contact surface area is to be enlarged, the result will give electric efficiency of 27.69 %.

5. Appendix

$$P_{H_2} = N_{H_2} * \Delta H$$

$$Q_{gas} = \overline{N}_{gas}.R.\int_{T_A}^{T} (\alpha + \beta.^{T} + \gamma.T^2 + \delta.T^3 + \varepsilon T^4).dT$$

Gas	A	$\beta.10^3$	$\gamma.10^4$	$\delta.10^5$	$E.10^6$
H_2	3,057	1,487	-1,793	0,947	-0,1726
H_2O	4,070	-0,616	1,281	-0,508	0,0769
O_2	3,626	-1,043	2,178	-1,160	0,2053
N_2	3,675	-0,671	0,717	-0,108	-0,0215

Motor power of pump, blower or compressor, and fan as follows:

$$P_x = \frac{Wx}{\eta_{motor}} \qquad x = \text{pump, comp, fan}$$

$$W_{com\ fan} = Q_c + \overline{m}.\left[(h_1 - h_2) + \left(\frac{V_1^2 - V_2^2}{2}\right)\right]$$

$$W_{pump} = \overline{m}.\left[(h_2 - h_1) + \frac{V_2^2 - V_1^2}{2} + g.(Z_2 - Z_1)\right]$$

Molar humidity $$Y_{mol} = \frac{mol, H_2O}{mol.G} = \frac{P_{H_2O}}{P_t - P_{H_2O}}$$

Saturated molar humidity: $$Y_{S,mol} = \frac{P^o_{H2O}}{P_t - P^o_{H2O}}$$

Relative humidity: $$RH = \frac{Y_{mol}}{Y_{S,mol}}.100\% = \frac{mol.H_2O}{(mol.G).Y_{S.mol}}.100\%$$

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